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Differences in Aircrew Manual Skills in Automated and Conventional Flightdecks

ABSTRACT
Aircraft flightdecks have become highly automated in the effort to maximize aircraft performance, increase terminal area productivity, and reduce fuel costs. While flightdeck automation offers significant operational advantages over older conventional flightdecks, unintended side effects due to automation have been observed. Among these concerns is the possible change of pilot basic skills in automated aircraft. This study sought to determine what, if any, possible differences exist in manual flight skills between aircrews assigned to conventional and automated flightdecks. Commercial airline crew members flying the conventional transport aircraft or the automated version were observed during line-oriented-flight-training. Aircraft state and pilot control inputs were recorded for analysis. Statistically significant differences in manual control inputs were found, particularly during abnormal operations. The results from this study have implications regarding modification of aircrew recurrency training, standard operating procedures, and flightdeck resource management in order to further optimize aircrew performance and safety in automated flightdecks.

INTRODUCTION

The increased capabilities of modern transport aircraft, complexity of operations in today's congested environment, and recognition of human limitations has spurred aircraft designers to automate flightdecks. Modern aircraft require more skillful handling due to their speed, weights, and the criticality of flight regimes. Furthermore, standard instrument departures, standard terminal arrivals and noise abatement procedures have become more complex, thus placing increased demands on pilot and aircraft performance.

Among the many possible assets of flightdeck automation are the ability to increase overall system efficiency by improving terminal area productivity and fuel economy while simultaneously increasing safety levels. Specifically, Wiener (1) suggests the following advantages that flightdeck automation offers:

Increased capacity and productivity
Reduction of manual workload and fatigue
Relief from routine operations
Relief from small errors
More precise handling of routine operations, and
Economical utilization of machines.

Undeniably, automation has extended the capabilities of aircraft, but the complexity of piloting has correspondingly increased. An industry-wide study (2) produced the "National Plan to Enhance Aviation Safety Through Human Factors Improvements" and identified the following issues that need attention with regard to automated aircraft:

Introduction of unanticipated failure modes
Potential for substantially increasing "head-down" time,
Reluctance of flight crews to take over a malfunctioning system,
Complacency, lack of vigilance, and boredom in pilots,
Increases in terminal area workload,
Incompatibility with present ATC System,
Difficulty in recovering from automation failure, and
Deterioration of pilot basic skills.

Flightdeck automation has rapidly changed the nature of the flying task by placing a number of computer based devices at the pilots' fingertips, thereby replacing the demand for manual control. Both management and line pilots are concerned about a possible change in flying skills due to the use of automation. Over half of the Boeing 757 pilots and 77% of the McDonnell Douglas MD-88 pilots interviewed by Wiener (3) stated concerns about the possible loss of aviation skills with too much automation.

The concerns of these pilots is not without merit. The man/machine interface has been cited in recent accidents of automated aircraft. (4-9) Fifty-six percent of all non-fatal, pilot-caused accidents are due to defective perceptual motor activities, such as aircraft control, judging distance and speed, etc. (11-12) Nagel (13) notes that the bandwidth a pilot can achieve is very much a function of the degree to which the control skill is practiced. Furthermore, an analysis of U.S. Air Force accident rates during training (14) reveals that the accident rate experiences a temporary spike immediately following leave periods, leading to the conclusion that the complex skills required to pilot a jet aircraft must be practiced at regular intervals in order to maintain proficiency. Experienced line and management pilots feel that pilots must maintain their basic flight skills because of five factors present in today's operational environment. Very few will question the concept that skills, especially the complex skills required to fly transport jet aircraft, must be regularly practiced in order to maintain a proficient level.

Second, in today's congested airspace with rapid-fire clearances, it is not at all uncommon for flight crews to become so task saturated with attempting to program the last minute changes into the flight management systems (FMS) that many crews have found it much easier (and safer) to simply revert to manual control.

Third, with the increase in high density traffic at congested airports, last minute speed and altitude adjustments will continue to increase, thus causing the frequent "slam-dunk" maneuver which places a premium on the aircrew's ability to maximize the performance of the aircraft in a high workload environment. Hendricks (15) states that such maneuvers place a premium on the pilot's basic aircraft motor skills, perceptual skills, and judgment.

Fourth, physical flying skills are one of five critical elements of situational awareness. Schwartz (16) states that flying the aircraft remains the highest order of priority, regardless of other demands for a pilot's attention. Maintaining flying proficiency allows a pilot to devote less mental energy to flying the aircraft, thus allowing more attention to be devoted to other needs.

Fifth, flightdeck automation will continue to be implemented into ever increasing numbers of commercial aircraft.

OBJECTIVES

This study seeks to complement other studies involving automated flightdecks so that future training programs and operating procedures may be updated in order to increase the safety and efficiency of future air transport systems.

Therefore, this study seeks to determine the following research questions:

1) To what degree do manual flying (aircraft control) skills differ between aircrews in automated and conventional flightdecks during normal and abnormal operations in terminal airspace?

2) To what degree do navigational tracking skills differ between aircrews in automated and conventional flightdecks during normal and abnormal operations in terminal airspace?

METHODOLOGY

Experimental Subjects

This study was designed as a one-factor experiment divided into two independent groups: conventional-flightdeck pilots and automated-flightdeck pilots. All experimental participants were commercial airline pilots holding airline transport pilot certificates. A total of 48 subjects (24 aircrews;

12 aircrews from each type of aircraft) were evaluated. The groups were divided by classification according to the automated or conventional type of aircraft flown. The two aircraft considered were virtually equal in all other parameters except for the degree of automation employed in the flightdeck. Measurements were taken of both captain and first officer flight performance during simulator training.

All data collection was performed during the afternoon training period in order to reduce circadian effects for aircrew members who live at various domociles through the continental U.S.

Population Demographics

Aircrews evaluated in this study were chosen by the crew scheduling department based upon the need for annual training required by Federal Aviation Regulations. The schedule is primarily dictated by date of hire of the aircrew members. It was assumed that there is no method of aircrew assignment which would bias the backgrounds of either conventional or automated group.

Aircrew total flight experience and experience in the specific type of aircraft did not differ markedly between the two groups. Table 1 summarizes the distribution of experience for both groups.

Experimental Device

This investigation was conducted using Phase III six-degree-of-freedom motion simulators of the commercial transport aircraft. The simulator cabs were equipped with instrumentation for VFR and IFR takeoff and landing tasks as well as throttle, gear, and flap controls to allow accomplishment of a wide variety of in-flight maneuvers. The cabs are also equipped with hydraulically actuated control loaders, programmed to give the desired dynamic force-feel characteristics of the aircraft during various phases of flight.

The pilots in the cab were provided with visual, aural and motion cues. The visual cues give a 50 degree wide collimated display to both pilots. A field of view of 150 degrees wide and 40 degrees high is produced using three calligraphic projectors, each driven from three computer generated image channels.

Measures of Manual Performance

Maneuvers

Pilots of both groups, as part of their annual recurrent training, are required to accomplish certain maneuvers. This investigation studied the following terminal area maneuvers:

Takeoff and Initial Climb (normal),
Continued Takeoff with Engine Failure and Initial Climb,
Instrument Landing System (ILS) Approach and Landing (normal), and
Single Engine ILS Approach and Landing.

Dependent Variables

Crew performance is currently assessed according to four major areas. Communications process and decision behavior, team building and maintenance, workload management and situational awareness, and overall technical proficiency comprise the four major markers of crew performance. Adherence to FAR/ATC directives, stick and rudder skills, checklist usage and systems knowledge are the areas graded within overall technical proficiency. [17]

This report addresses only the "stick and rudder" portion of overall technical proficiency. The dependent variables used for evaluating individual pilot performance included aircraft state variables and pilot control inputs. The aircraft state and pilot control variables evaluated in this study were the following:

aircraft pitch and bank attitude,
aircraft indicated airspeed, heading and altitude,
aircraft displacement from glide slope and localizer, and
pilot control inputs (elevator, throttles, ailerons, and rudder.)

At the start of each of the above maneuvers, an observer, who was present in the simulator during the training sessions, initiated an algorithm in the simulator's software which recorded the aircraft and pilot inputs for later analysis. The selected parameters were recorded at 10 Hz over the time interval. Aircraft net deviations across the time interval were calculated as the deviation of the instantaneous pitch and bank angle from the time averaged value. This provided a measure of the closeness with which the pilot maintained the average aircraft pitch and bank throughout the maneuver. The time averaged value was calculated using the signal's root-mean-square.

Comparison of airspeed deviations from the final approach speed were calculated as follows:

(1)

Glide slope and localizer deviations across the time interval were calculated as follows:

(2)

De-Identification

All information was immediately deidentified so that no one set of data could be traced back to an individual. The databases were secured and personal identifiers removed before publication and release of any findings. No information regarding any individual crewmember or the participating air carriers can be released.

Test of Statistical Significance

The t test was used as the measure of statistical significance. The experimental null hypothesis for this study assumes that no difference exists between the two population means. Specifically, this tests the following hypothesis:

$H_o: \mu_1 - \mu_2 = 0$

Using the Cochran-Cox method, the value of t required for an $\alpha = .05$ level of significance is 2.069. An observed value of t greater than 2.069 is grounds to reject the null hypothesis, with a confidence of 95%. Rejecting the null hypothesis is tantamount to acknowledging a statistical difference in the two population's means.

FINDINGS

Normal Takeoff Performance

During normal takeoffs, the automated crew members exhibited an average of 7.4 pitch oscillations after rotation from takeoff while establishing climb out speed, whereas conventional crew members exhibited an average of 3.2 pitch oscillations. Automated crews exhibited a mean of 4.3 bank overshoots in turning to the assigned heading on takeoff, while conventional crews exhibited a mean of .8 overshoots. Maximum bank angle deviations during climb out averaged 14.5 degrees for the automated crews versus 3.2 degrees for conventional crews. Automated aircrews averaged a 150.2 foot deviation from the assigned altitude on level off, whereas conventional crews averaged 40.0 feet.

The normal "t" test for the significance of the differences between means assumes equality of the population variances. In this study, the assumption of equality of variances is untenable. Therefore, the method of Cochran and Cox is used to make an adjustment in the value of t required for significance at the 5% level. Table 2 summarizes point estimates of the mean, 95% confidence interval estimates, and "t" tests of statistical significance of these parameters. Using the Cochran-Cox method, the t-test of statistical significance requires a value of 2.069 for a 95% confidence estimate. The actual t test values for airspeed and pitch are 15.11 and 7.07 respectively. Clearly, these show significant differences between the means of the two groups.

Bank and heading information yields similar results. Mean deviations of bank angles for the conventional and automated aircrews were 129.4 and 244.2 deg-sec respectively, while mean deviations of the heading from the assigned value were 207.9 and 498.3 deg-sec, respectively. Conventional aircrews demonstrated smaller areas of deviation from the nominal bank angle during takeoff and climbout, resulting in smaller heading deviations from assigned values. The practical interpretation of these data is that conventional aircrews demonstrate smaller deviations from the nominal bank angle, resulting in smaller deviations from the assigned heading.

The "t" test values for heading and bank are 12.18 and 6.46 respectively. These show significant differences between the means of the two groups, thus indicating that statistically significant differences exist between the manual piloting skills of the two groups during normal takeoffs.

Normal ILS Approach

Numerical analysis of landing parameters included a summation (see Equations 1 and 2) of the deviation of the airspeed, glide slope position, localizer position, bank angle and pitch attitude from nominal values (Table 3.)

With the autothrottle disengaged, automated crews showed a root-mean-square deviation of 13.6 knots from the final approach speed, with individual maximum deviations ranging from 15.8 knots fast to 13.3 knots slow. Conventional crews showed an average deviation of 5.2 knots, with individual maximum deviations ranging from zero to 8 knots. The mean of the deviations for the conventional and automated groups was 257.8 and 928.8 knots-sec, respectively. The conventional group again showed less variation within the group than the automated group.

From an operational standpoint, airspeed deviation is perhaps the most significant finding of this study. Without a forward mounted camera to detect eye motion, it is unknown whether the automated group's instrument scan has left the airspeed indicator out of their scan. The cause for these airspeed deviations deserves further study.

The average area of the glide slope deviation across the time interval was 11.8 and 24.6 deg-sec for the conventional and automated groups, respectively. Conventional and automated aircrews demonstrated 22.1 and 50.2 deg-sec deviation from the nominal pitch attitude during the normal ILS approach.

Localizer and bank attitude data show similar trends. The root-mean-square value of the deviation from the centerline of the localizer was 26.0 and 54.0 deg-sec for the conventional and automated groups. Mean bank deviations were 67.7 and 207.7 deg-sec for the conventional and automated groups.

The "t" test values between the means were 15.97 for airspeed, 8.70 for glide slope, 11.68 for localizer, 9.66 for bank and 9.58 for pitch differences. Clearly this indicates a statistically significant difference between the group means for these parameters. This is tantamount to stating that there is a statistically significant difference in the manual skills between the two pilot populations.

V-1/Continued Takeoff Performance

Performance measurements of aircrew performance during the V-1/continued takeoff, summarized in Table 4, display similar trends reported earlier for the normal takeoff. Note that conventional aircrews showed smaller airspeed and pitch deviations during this critical maneuver than during normal takeoffs. The areas of airspeed deviations during normal and V-1 takeoffs were 214.8 and 199.4 knots-sec respectively. This would indicate heightened awareness by the aircrews of the criticality of this maneuver, and the ability of the aircrew member to fly the aircraft even more precisely with respect to pitch and airspeed control. However, heading and bank control did suffer during the engine-inoperative climb. This is not unexpected due to the large yawing moment produced by asymmetrical thrust.

Automated group performance displayed greater deviations from assigned parameters than the conventional group. The means of the areas of the airspeed deviations are 793.3 and 199.4 knot-sec respectively for the automated and conventional groups. Pitch motions demonstrate similar differences between 64.6 and 21.4 deg-sec for the automated and conventional groups.

Heading deviations were 232.1 deg-sec in the conventional group, versus 618.8 deg-sec in the automated group. Bank deviations were 146.0 deg-sec in the conventional group, versus 304.4 deg-sec in the automated group.

Tests of statistical significance yielded "t" values of 15.1 for airspeed deviations, 15.78 for pitch deviations, 14.76 for heading deviations, and 9.29 for bank deviations. These values of "t" are more than sufficient to reject the null hypothesis, leading to the conclusion that statistically significant differences exist in manual piloting skills between the two pilot populations during engine inoperative takeoffs.

Unlike the conventional group, which showed only small increases in deviations during this maneuver when compared to the normal takeoff, the automated group's performance showed a large increase in deviations from assigned parameters. The automated group's mean area of the airspeed deviation increased from 534.2 to 793.3 knots-sec. The automated group's mean pitch deviation increased from 45.5 to 64.6 deg-sec, corresponding to the airspeed deviations.

Directional control difficulties during the V-1/continued takeoff maneuver were also manifested by larger heading deviations and bank. Heading deviations within the automated group increased from 498.3 deg-sec during the normal takeoff to 618.8 deg-sec during the engine failure/V-1 continued takeoff maneuver. Bank deviations showed similar trends, increasing from 244.2 deg-sec to 304.4 deg-sec.

Engine-Inoperative ILS

Table 5 summarizes the differences in aircrew performance during the single engine ILS maneuver. The conventional group showed very little change in airspeed, glide slope and localizer control between the normal and single engine ILS. Airspeed deviations were 257.8 versus 257.9 knot-secs between the normal and single engine ILS maneuvers. Glide slope deviations were 11.8 and 11.9 deg-secs, and localizer deviations were 27.1 versus 26.0 deg-secs for the normal and single engine ILS maneuvers.

The automated group showed larger increases in performance deviations during the single engine ILS as compared to their performance during the normal ILS. Airspeed deviations increased from 928.9 to 989.2 knot-secs. Glide slope deviations increased from 24.6 to 25.9 deg-secs, and localizer deviations increased from 54.0 to 61.9 deg-secs.

Comparison of the performances of the conventional and automated aircrews during the single engine ILS yields similar findings as previous maneuvers. Airspeed deviations were 257.9 knots-sec for the conventional group, and 989.2 knots-sec for the automated group. Means of the glide slope deviations were 11.9 deg-sec for the conventional versus 25.9 deg-sec for the automated groups. Localizer deviations were 27.1 deg-sec for the conventional group, and 61.9 deg-sec for the automated group.

Test of statistical significance yielded "t" values of 15.56 for airspeed deviations, 9.19 for glide slope deviations, and 11.09 for localizer deviations. Each of these values is indicative of statistically significant differences between the automated and conventional groups during single-engine ILS approaches.

CONCLUSIONS AND RECOMMENDATIONS

Tests of statistical significance confirm observations that significant differences exist between the manual performance of the automated and conventional groups. Analysis of aircraft state parameters leads to the conclusion that pilots of automated aircraft, while flying the aircraft manually during these maneuvers, consistently exhibited greater deviations from assigned courses and aircraft state parameters, and greater deviations from nominal pitch and bank attitudes, than do pilots of conventional flight deck aircraft.

Approach and Landing Conclusions

The most significant differences were found to occur during the approach and landing phases. It is industry practice to tolerate very little airspeed deviation from the recommended value during approach and landing. The FAA's Practical Test Standards for the Airline Transport Rating allow only a five knot margin faster than the recommended final approach speed. The Practical Test Standards also require a stabilized final approach with no more than one-quarter scale deflection of either the glide slope or localizer. NTSB accident records [18-24] list unstabilized approaches as a causal factor in a disproportionate number of accidents, further confirming the importance of stabilized approaches. Variations in airspeed during final approach result in changing aim points during the very dynamic process of landing, where a great majority of major mishaps occur. This makes it more difficult for the pilot to predict the actual touchdown point.

The safety consequences, especially in terminal airspace, of these larger deviations deserve attention and suggest intervention strategies to prevent automated aircrew manual performance from diverging further from conventional aircrew performance.

Short Term Intervention Measures

Perhaps the simplest solution to this problem is to encourage automated aircrew members to manually fly a certain percentage of departures and arrivals. While that seems to be the clear cut solution to the entire question of this study, the authors are not convinced that the entire difference in performance is due solely to the lack of practice by the automated group. Or stated another way, the authors are concerned that this simple recommendation may only address a symptom and not the underlying cause(s).

Since the need to fly a stabilized approach is so critical, this study recommends not only short term measures, but also a series of investigations which will fully examine the effects of flightdeck automation on all of the integrated aspects of the air transportation system.

Within the short term, this study recommends a judicious balance of automated and manual departures and arrivals to optimize safety and maintain pilot manual skills. Crew resource management must be amended specifically for the automated flightdeck.

Long Term Intervention Measures

The effects of the current ATC system coupled with the use of automated flightdecks must be examined. Findings from this study and others (1,2,3) suggest that pilot workloads increase for automated aircrews during maneuvers in terminal airspace, partly due to the incompatability of automation with the current ATC system. The design of the future ATC system must take into account how to interface efficiently and safely with automated flightdecks.

Single Engine Operations

Swept wing aircraft are strongly coupled between rolling and rudder input. Very slight rudder inputs, especially with a failed engine, can produce significant bank angles. Whenever the throttle is adjusted, a corresponding rudder movement must occur. This in turn can produce a banking motion which many times was not compensated for by the automated aircrews. Because of problems with rudder inputs, the aircraft pitch and bank attitudes in the automated group deviated more from nominal values.

Further Study

As stated in the introduction, the deterioration of pilot manual skills is one of the noted concerns with flightdeck automation. If the reader assumes that the manual skills of both groups were equal upon assignment to their respective fleets, then one can surmise that the manual skills within the automated group has diminished over time. However, to more exactly address this question, a long term study measuring the manual skills of automated aircrews over time is required.

Due to the greater variance in performance within the automated group, other variables such as pilot total time, pilot background (type of aircraft flown in past, etc.) percentage of flight time in manual versus automated modes, number of hand-flown approaches in the last six months, and time in type should be compared in future reports to determine if any of these parameters may cause a statistically significant variation in performance within the automated population. An analysis of variance investigation will then be possible to determine the methods by which automated crews are best able to maintain manual proficiency.

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